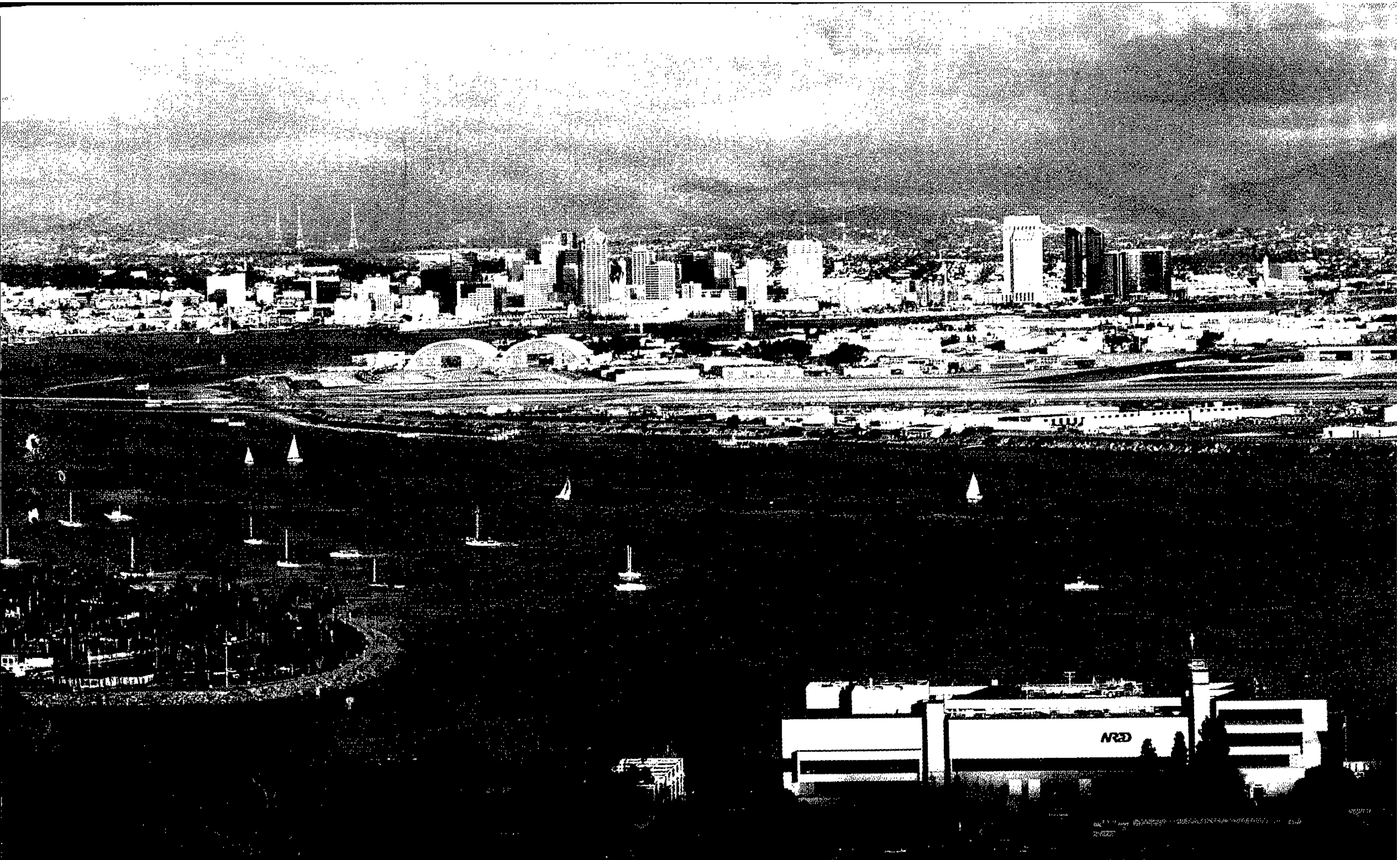

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Potentials for Navy Use of Microwave and Millimeter Line-of-Sight Communications

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

Line-of-sight (LOS) communication links can be used to provide a battlegroup with an internal data networking capability with sufficient data throughput to accommodate modern information transfer requirements (voice, video, and data). As frequency bands below 2 GHz become fully populated, the communications systems designer must look at higher frequency bands to achieve these goals.

This report investigates the use of LOS communications in the microwave and millimeter frequency bands (2 GHz to 90 GHz) to support data rates greater than 10 Mbps. Issues relevant to communications in this frequency band were investigated, such as weather effects, LOS blockage, and the need for high-gain directional antennas. Additionally, Navy-specific issues were investigated, including size and weight limitations, shipboard electromagnetic interference sources, and antenna stabilization aboard moving platforms.

It was found that extremely high data rates (up to 225 Mbps) might be possible for point-to-point, intra-ship communication at frequencies between 2 and 30 GHz. Rain attenuation is predicted to severely degrade communications ranges at frequencies above 30 GHz. In addition, recent technological advances in commercial microwave and millimeter communications afford the Navy an opportunity to expand its communications capabilities, perhaps with only minor equipment modifications.

Issues requiring further investigation include antenna placement and the creation of wireless communications networks requiring multiple high-data-rate links off each platform.

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INTRODUCTION

BACKGROUND

As the Navy uses more sophisticated sensors and information networking equipment aboard its ships, its data transfer requirements increase. To operate with greater efficiency, modern battle-groups must share larger amounts of targeting, tactical, and administrative data in real time. Current communications systems are limited in their ability to transfer data, both by their allowed frequency bandwidths and by the interference inherent in the frequency bands currently in use. The frequency spectrum from 2 MHz to 2 GHz, where most Navy communications are located, is crowded with communications signals generated by commercial users and radar signals. Further, international regulations limit the amount of bandwidth available to a single user. Higher frequency bands are more sparsely populated. At frequencies above 2 GHz, available bandwidth increases as well. Until recently, the technology did not exist to provide small, inexpensive communications equipment above 2 GHz.

Point-to-point communications in the microwave and millimeter frequency bands, particularly frequencies from 2 GHz to 90 GHz, are becoming more common for commercial applications as commercial firms invest more in communications research and new equipment development. The resultant improvements in communications technology can be applied to Navy needs to provide very high-data-rate, line-of-sight (LOS) communications links for ship-to-ship and ship-to-shore use. Advances in communications technology in these frequency bands is also making available small, lightweight, and relatively inexpensive systems that can be modified for use on Navy platforms.

In addition to the normal characteristics of microwave and millimeter communications, such as weather effects and the need to use directional antennas, Navy communications places additional requirements on such systems. The need to function aboard moving ships, and antenna location and size restrictions, are chief among the reasons for the additional requirements. Technological improvements in commercial communications have produced candidate systems that could be modified for Navy use. Antenna pointing systems used aboard commercial aircraft and recreational vehicles for Direct Satellite System (DSS) television signal reception might provide the basis for a Navy shipboard system. Millimeter communications gear used for commercial trunking systems seem to be able to provide the foundation for lightweight, inexpensive Navy communications systems.

Microwave and millimeter frequency bands can provide the Navy with digital communications with data rates from 1.544 Mbps (T1) to 225 Mbps. Commercial technological advancements appear to be able to provide the Navy with a foundation on which shipboard systems could be produced.

SCOPE

This technical report attempts to answer the question: How can the Navy make use of LOS communication links in the microwave and millimeter frequency bands, with frequencies ranging from 2 GHz to 90 GHz? Issues relevant to communications in this frequency band are addressed, such as weather effects, LOS blockage, and the need for high-gain directional antennas. Additionally, Navy-specific issues are discussed, including size and weight limitations, shipboard electromagnetic interference sources, and antenna stabilization aboard moving platforms.

The author assumes that the reader has a general familiarity with communications theory. The report breaks down hypothetical communication systems to the subsystem level. Modems and

receivers are discussed; modem microchips and local oscillators are not. A list of references and a bibliography provide the reader with more in-depth information about the subjects discussed in this report.

MOTIVATION

Higher data rates require greater bandwidths in general. The frequency spectrum currently allocated to the Navy for LOS communications has severe bandwidth limitations, both by international agreement and the scale of international use. Navy satellite communications capacity is limited and is typically used for long-haul communications from the battlegroup to shore facilities and command centers. While commercial satellite capacity can make up for some of this deficiency, it is less robust than military systems, and as global fiber-optic cable connections become more common, fewer commercial satellites designed to provide high-data-rate channels may be launched to replace those that attrit due to age or obsolescence (Poisel & Hogler, 1993).

It makes sense, then, to examine how LOS communications links can be used to provide a battlegroup with an internal data networking capability with sufficient data throughput to accommodate modern information transfer requirements. As lower frequency bands are fully populated, the communications systems designer is forced to look at higher frequency bands to achieve his goals. This report assesses the frequency spectrum from 2 to 90 GHz for LOS communications.

DISCUSSION

CHANNEL CHARACTERISTICS

At frequencies above 2 GHz, radio wave propagation is predominantly by line-of-sight. Certain atmospheric conditions can occur that cause ducting which essentially "bend" the radio waves around the curvature of the earth. Unlike communications in lower frequency bands, atmospheric noise contributes negligible amounts of interference. Instead, multipath effects from replicas of the transmitted radio waves shifted in phase and amplitude from atmospheric and ground plane reflections can sum with the desired signal and partially cancel it. Partial or complete physical blockage of the LOS path can also severely attenuate the signal. Interference from man-made sources such as other communication signals and radars can also reduce communications link quality. Further, for frequencies above 10 GHz, water vapor in the air from rain or fog can attenuate the signal. Lastly, the absorption frequency of oxygen molecules, 60 GHz, lies within the frequency range of 2 to 90 GHz.

Radio waves can be refracted by a process known as ducting as they travel through the earth's atmosphere and bend about the surface of the earth, extending the range at which they can be received. The primary cause of this refraction is water vapor suspended in the atmosphere. If a communications link was strictly line of sight, its maximum range would be limited by the curvature of the earth and be given by the following equation:

$$d \cong 1.065\left(\sqrt{h_t} + \sqrt{h_r}\right), \tag{1}$$

where d is the range in nautical miles, h_t is the height of the transmitter antenna in feet, and h_r is the height of the receiving antenna in feet. When atmospheric refraction occurs and the radio waves follow the curvature of the earth to some extent, the communications link range is given by:

$$d \cong 0.922\left(\sqrt{Kh_t} + \sqrt{Kh_r}\right), \tag{2}$$

where K is the effective earth radius factor. The value of K can range from 0.6 to 5.0, but is typically taken to be 1.33 for temperate latitudes. (K less than 1 corresponds to an atmospheric refraction effect that reduces communications range.) Under certain conditions, this refraction can be even more severe than normal, and K attain values greater than 1.33. It is a relatively uncommon event, but can be used to achieve over-the-horizon radio communications. Ducting and its effects are well treated in James and Rockway (1990), Rockway and James (1991), and Rogers and Anderson (1993). Figure 1 shows a plot of the approximate maximum communications link range as a function of antenna height and K. These results are based on the radio horizon for transmission and reception antennas with equal heights above the surface of the water.

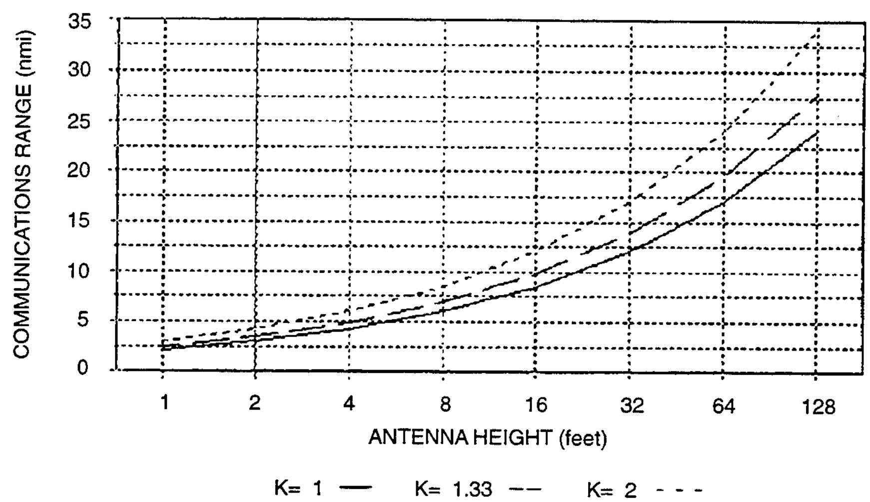

Figure 1. Maximum communications link range vs. antenna height and effective earth radius.

The transmitted signal can be reflected off of the earth's surface, man-made objects such as helicopter rotor blades, or atmospheric effects, shifted in phase and modified in magnitude, and be received by the receiving antenna. Such multipath effects can either improve communications link quality, if the reflected signal is close in phase to the unreflected signal, or degrade the link quality, if the reflected signal is close to 180 degrees out of phase with the unreflected signal. The magnitude of these reflections depends on the properties of the reflecting surface. A calm ocean, for example, will reflect the signal well, and the multipath component of the received signal may be nearly as strong as the unreflected signal. In such a case, if the reflected signal is shifted close to 180 degrees out of phase with the unreflected signal, it may nearly cancel out the desired signal, causing severe link degradation and even loss of synchronization. As another example, a choppy ocean, such as occurs in high winds, will reflect the signal poorly, and degradation due to the summing of an out-of-phase image of the desired signal may be negligible.

Objects that physically obstruct the signal's path can attenuate or completely block the communication signal. In some cases, such as urban environments, reflections of the signal off of other objects such as buildings can allow a receiver to acquire and demodulate the signal despite the fact that the primary signal has been blocked. For Navy applications, no such fortuitous circumstances

are likely to occur. Therefore, blockages, such as those caused by ship superstructures, will effectively eliminate communications. This means that to obtain complete coverage around the ship, either the antenna must be placed where no blockages occur, or multiple antennas must be used to completely cover all 360 degrees azimuth around the ship.

Man-made interference at this frequency band consists chiefly of radar signals, their harmonics, and associated spurious signals. Communications in this frequency range are typically directional and low power, so that interference from other communications signals would have to come from directly in front of the antenna and be within the same frequency band. The maintenance of the military communications spectrum is such that this is extremely unlikely to occur. Interference from radar signals can be significant. Many of the radars used aboard ship emit signals at power levels in excess of a kilowatt. Their harmonics and spurious signals, even if attenuated by 40 dB, can contribute significant background interference to the received signal. For this reason, it is crucial to locate the communications frequency sufficiently distant from the frequency bands used by radar.

Weather effects such as rain or fog can attenuate signals above 10 GHz. The attenuation in decibels per kilometer, described more fully in James and Rockway (1990) and Rockway and James (1991), is given by:

$$\alpha = a(f) RR^{b(f)}, \tag{3}$$

where

$$a(f) = G_a f^{E_a} \tag{4}$$

and

$$b(f) = G_b^{E_b}, \tag{5}$$

and RR is the rain rate in millimeters per hour. The values for G_a, E_a, G_b, and E_b are given in tables 1 and 2. Figure 2 plots the attenuation in dB/nmi as a function of frequency and rain rate. It can be seen that the effects of rain can degrade the maximum communication link range by severely attenuating the transmitted signal.

Table 1. Constants for rain attenuation variable, a(f).

Minimum Frequency (GHz)	Maximum Frequency (GHz)	G_a	E_a
0.00	2.90	6.39e-5	2.03
2.90	54.00	4.21e-5	2.42
54.00	180.00	4.09e-2	0.70

Table 2. Constants for rain attenuation variable, b(f).

Minimum Frequency (GHz)	Maximum Frequency (GHz)	G_b	E_b
0.00	8.50	0.85	0.16
8.50	25.00	1.41	–0.08
25.00	164.00	2.63	–0.27

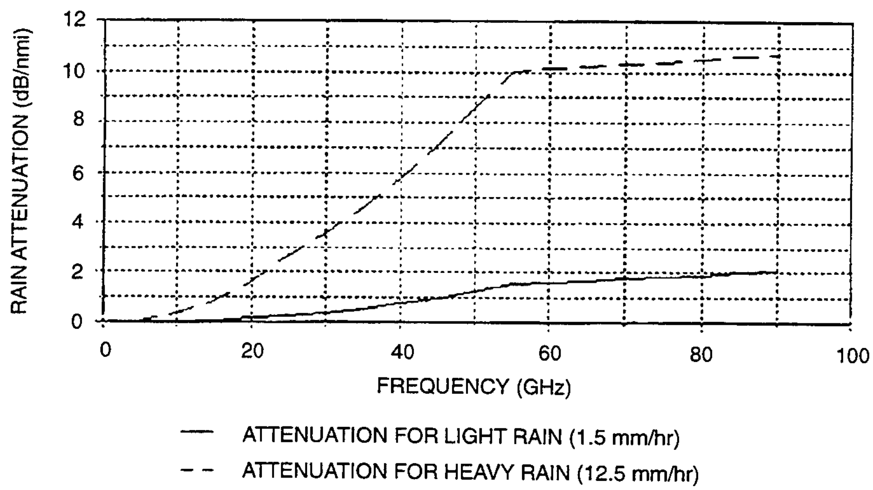

Figure 2. Rain attenuation with respect to rain rate and frequency.

Finally, the natural vibration frequency of oxygen molecules occurs within the millimeter spectrum. O_2 molecules vibrate at 60 GHz, and therefore these molecules naturally absorb energy at frequencies around 60 GHz. In fact, free-space absorption at that frequency is over 15 dB/km. For that reason, communications at and near 60 GHz are, for all practical purposes, impossible.

FACTORS FOR SHIPBOARD USE

In addition to all of the normal parameters affecting the use of microwave and millimeter communications, Navy communications and shipboard equipment installation add more complexities. The first, and perhaps most critical factor is antenna placement. As these systems provide LOS communications, the height of the antenna is a limiting factor of the maximum range obtainable by the system. Current communications and surveillance radars typically occupy a tremendous amount of topside space aboard ships and the ship's masts, and such structures are essentially fully populated with antennas. This means that in order to maximize the number of candidate locations for the antenna(s) required for these systems, their antennas must be made as small as possible.

Fortunately, small antennas can still provide sufficient gain, as shown later in this report. We base the margin and range calculations below on a parabolic dish antenna that is only 1 foot in diameter. As a comparison, the modern direct satellite system TV antennas are 18 inches in diameter.

Since these systems are line of sight and the antennas are directional, there must be a means of compensating for ship motion while a communications link is active. There are a large number of

alternative pointing systems for such antennas. In the discussion on antenna pointing systems given below, we show that a low-cost, commercial, two-axis antenna pointing system would likely be sufficient to provide ship-to-ship communications. These systems are small and lightweight, designed for use aboard commercial aircraft and motor homes. As such, locating space for their installation may not be as difficult as it is for larger antenna systems.

The costs of purchasing, installing, and maintaining systems is also a limiting factor. As military budgets decrease, the viability of new, expensive communications systems decreases as well. Fortunately, the components that make up the systems described below are typically available and relatively inexpensive, requiring little or no development or modifications for shipboard use. Candidate systems are described in appendix A.

While shipboard use introduces several complexities to the design, installation, and use of microwave and millimeter LOS systems, none of these difficulties are intractable. The advantages of such systems in increased throughput and small size make these attractive candidates to provide the Navy with modern, high-speed battlegroup communications.

FREQUENCY BAND ALLOCATION

By international agreement, the frequency spectrum has been divided into frequency bands, whose general operating usage is defined by the International Telecommunications Union (ITU). Usage categories include mobile communications (including ships), satellite communications, radio navigation (radar), radio astronomy, and fixed communications. These allocations are amply described in Van Valkenberg (1993).

Navy LOS communications typically fall under the category of mobile communications. Table 3 gives an excerpt from the ITU frequency allocation table, showing the frequency bands from 2 to 90 GHz that have been allocated at least partially to mobile communications. The width of these bands is of particular interest. A communications link that would give up to 225 Mbps performance would require on the order of 225 MHz in bandwidth. From table 3, it is apparent that as frequency is increased, the likelihood of finding a candidate frequency for the communications link increases as well.

Table 3. ITU spectrum allocations for mobile communications from 2 to 90 GHz.

Start Frequency (GHz)	Stop Frequency (GHz)	Width of Frequency Band (GHz)
2.00	2.20	0.20
2.29	2.69	0.40
4.40	5.00	0.60
5.85	8.50	2.65
10.50	10.68	0.18
10.70	11.70	1.00
12.75	13.25	0.50
14.40	15.35	0.95

Table 3. ITU spectrum allocations for mobile communications from 2 to 90 GHz. (Continued)

Start Frequency (GHz)	Stop Frequency (GHz)	Width of Frequency Band (GHz)
17.70	19.70	2.00
21.20	23.60	2.40
25.25	27.50	2.25
31.00	31.30	0.30
36.00	40.50	4.50
42.50	47.00	4.50
47.20	51.40	4.20
54.25	58.20	3.95
59.00	64.00	5.00
66.00	75.50	9.50
81.00	86.00	5.00

While there is a large portion of the spectrum devoted to mobile communications, some of it has already been dedicated to commercial communications for frequencies below 2 GHz. This is true in a global sense as well, with commercial mobile communications frequency allocations varying from country to country. Typically, the most heavily used frequencies for cellular and related mobile communications are around 850 MHz and 1.9 GHz.

While great care is taken to separate radar and communications, sometimes the great power of radar systems cause their harmonics to be significant well outside their allotted spectrum. For communications system design, it is crucial to understand where in the frequency spectrum candidate interferer radars operate and with what power. Table 4, from NAVSEA (1982), gives a sample set of U.S. Navy radars, their frequency bands, and typical operating power. Note that the power typically decreases as frequency increases.

Table 4. Shipboard radar characteristics.

Name	Frequency Range (MHz)	Emission BW (MHz)	Average Power (W)
SPS-43	205–225	0.33	9000
SPS-29	215–225	0.80	2800
SPS-37	215–225	0.80	9000
SPS-40	402–448	0.05	3600, 4400
SPS-49	851–942	0.40	10,000
SPS-58	1215–1365	10.00	180
SPS-58A	1215–1365	0.40	250

Table 4. Shipboard radar characteristics. (Continued)

Name	Frequency Range (MHz)	Emission BW (MHz)	Average Power (W)
SPS-65	1215–1365	30.00	250
SPS-10	5450–5825	1.6, 8.0	160
SPS-67	5450–5825	2, 8, 20	95–306
BPS-11	8740–8890	1.80	30
BPS-12&14	8795–8855	1.80	20
BPS-15	8795–8855	5.00	13
SPS-53	9345–9405	10, 61	19
SPS-55	9050–10,000	2, 16	98

LINK BUDGET CALCULATION

One can directly compute the quality of a communications link through a link budget calculation. This calculation takes into account all of the gains and losses of an end-to-end communications system and generates a measure of signal strength. In commercial communications, this calculation can be used to determine the locations of cellular communications repeaters, the required antenna size for LOS communications links, or even the power amplifier required to operate a wireless mouse away from a personal computer.

For the frequencies in question, this calculation has been done with some rigor (James & Rockway, 1990; Rockway & James, 1991) and is encapsulated here.

$$M_{dB} = P_T + G_T + G_R - L_{FS} - L_{PF} - L_R - N_D - D_R - REQ\,, \tag{6}$$

where M_{dB} is the link margin in dB,
P_T is the power in dBW developed by the system transmitter,
G_T is the effective transmitter gain in dB, including the gain from the transmitting antenna,
G_R is the effective receiver gain in dB, including the gain from the receiving antenna,
L_{FS} is the free-space loss in dB for the link,
L_{PF} is the additional propagation loss in dB above the free-space loss,
L_R is the additional loss in dB due to hydrometeor effects such as rain and fog,
N_D is the receiver noise density in dB, also called the receiver's noise figure,
D_R is the data rate in dB in Mbps, and
REQ is the required energy-per-bit-to-noise density in dB for the desired quality of digital communications.

The free-space loss is further defined as:

$$L_{FS} = 32.45 + 20\log(r) + 20\log(f), \tag{7}$$

where r is the range between transmitter and receiver in kilometers, and f is the center frequency of the signal in megahertz.

The link margin as a function of frequency is given in table 5, with the following conventions: The transmitter produces 1 watt of power, so that $P_t = 0$ dBW. The transmitting and receiving antennas are 1-foot-diameter parabolic dishes. Their gain is given in table 5. The range of the link is 20 nautical miles, so equation (7) reduces to $L_{FS} = 62.55 + 20 \log(f)$.

Table 5 has a column showing the free-space (FS) loss as a function of frequency. We assume that there are no propagation losses above free-space losses, so that $L_{PF} = 0$ and $L_R = 0$. James and Rockway (1990, 1991) develop a typical value for the receiver noise density in some detail, and we will use the results given therein, $N_D = 230.6$. The data rate is 225 Mbps, so that $D_R = 10 \log(225) = 23.52$ dB. Lastly, we assume that the modem is using a quadrature phase-shift keyed (QPSK) modulation scheme, where the required bit-error rate (BER) is 1.0e-6 and the required Eb/No is $REQ = 16$ dB.

Table 5. Link margin for 225-Mbps link assuming only free-space propagation losses and a constant 0-dBW transmit power using a 1-foot parabolic antenna.

Frequency (GHz)	Antenna Gain (1-foot-diameter)	FS Loss (20 nautical miles)	Margin (1 Watt)
5.00	21.06	136.59	36.61
10.00	27.08	142.61	42.63
15.00	30.60	146.13	46.15
20.00	33.10	148.63	48.65
25.00	35.04	150.57	50.59
30.00	36.62	152.15	52.17
35.00	37.96	153.49	53.51
40.00	39.12	154.65	54.67
45.00	40.14	155.67	55.69
50.00	41.06	156.59	56.61
55.00	41.89	157.41	57.44
60.00*	42.64	158.17*	58.19*
65.00	43.34	158.87	58.89
70.00	43.98	159.51	59.53
75.00	44.58	160.11	60.13
80.00	45.14	160.67	60.69
85.00	45.67	161.20	61.22
90.00	46.16	161.69	61.71

*Oxygen molecules absorb energy at 60 GHz. Radio wave propagation at this frequency does not obey the free-space loss equation given above, and the margin is actually far lower than stated.

Previously, we discussed attenuation of the signal as a function of rain rate and frequency. As the attenuation per nautical mile can be great at higher frequency, we now analyze how well the margin calculated above serves to overcome the effects of rain. Figure 3 shows a comparison of rain attenuation per nautical mile vs. margin per nautical mile, calculated for a 20-nautical-mile link and 225 Mbps. As the data rate and range decrease, the margin per nautical mile curve rises. The point at which the attenuation per nautical mile curve intersects the margin per nautical mile curve is the frequency at which communications become impossible at that rain rate. For the case shown below, the margin is high enough to overcome the attenuation due to light rain for all frequencies. For heavy rain and a 20-nautical-mile range, 225-Mbps communication is impossible above about 30 GHz using the previously detailed system parameters.

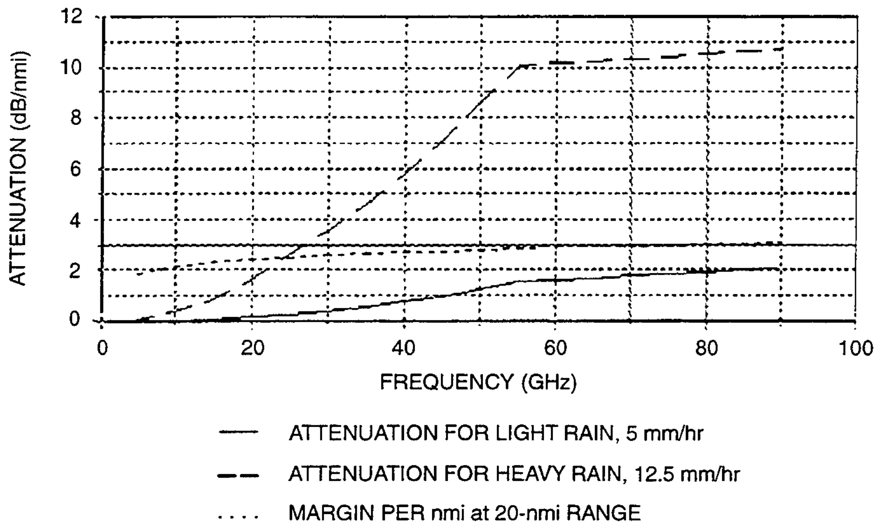

Figure 3. Rain attenuation per nautical mile vs. margin per nautical mile (20-nmi link, 225 Mbps).

ANTENNA REQUIREMENTS

Unlike commercial microwave or millimeter communications where antenna locations are fixed, and most communications link parameters are constants, Navy applications must deal with a wide variety of antenna installation and positioning variables. Among these variables are the changing distance between nodes, motion of the antenna platform, moving LOS blockages, and variable and possibly severe fading. Preparing for most of these can only be done by designing the system to have greater margin than a land-based commercial system would have. For antenna platform motion, an antenna pedestal that can point the antenna at a particular spot while the platform is moving must be used.

McDonald (1993) gives an excellent summary of ship motion as a function of sea state and ship type. Ship motion is defined in terms of total angular displacement as well as angular velocity for roll, pitch, and yaw. Angular motion is then classified into one of three categories as shown in table 6.

Table 6. Angular motion classified by category (continuous operation, limited operation, survival).

Ship Motion Category	Minimum Angular Velocity (degrees/ second)	Maximum Angluar Velocity (degrees/ second)	Notes
Continuous Operation	0.0	11.5	All equipment is expected to work to specifications.
Limited Operation	11.5	21.8	All equipment is expected to function, with some possible degradation.
Survival	21.8	26.5	Equipment critical to the survival of the ship is expected to work to specifications.

The entries in this table correspond to the worst-case hull in the fleet, typically that of a small ship such as a frigate or Coast Guard cutter. The larger ships such as aircraft carriers and amphibious assault ships are unlikely to experience large angular velocities. However, any system intended for use on all ships must be designed to meet the worst-case scenario.

There are several means by which a directional antenna can be mounted to overcome violent changes in ship orientation. The first is to use antenna pedestals with motorized gimbaling systems controlled by signal strength feedback systems. Modern systems in this category, such as the shipboard antenna pedestal used for the Navy EHF Satellite communications antenna, can track a stationary target while the ship is experiencing angular velocities up to 30 degrees per second, well above the thresholds given above. These systems, designed to point at targets whose elevation is unknown, rely on heavy and expensive three-axis controllers. That is, they must be able to counteract angular motion on all three spatial axes.

If the communication system was designed strictly for ship-to-ship communications, then the antenna would only need to point at the horizon. For circularly polarized signals, as most microwave and millimeter signals from directional antennas are, a system might only have to stabilize two axes, x and y, as shown in figure 4. The x-axis rotation would change the elevation angle of the antenna away from the horizon, and rotation on the y-axis would change the pointing direction on the horizon. The motion on the z-axis might not have to be counteracted, as it would not change the location in space where the antenna was pointing. Two-axis antenna pointing systems tend to be smaller, lighter, and less expensive than three-axis pointing systems. Commercial versions of two-axis antenna pointing systems have been developed for commercial aircraft and recreational vehicle applications.

If the antenna is designed with a wide beam angle, then the motion compensation specifications of the antenna pointing system can be relaxed. The antenna for the LAMPS helicopter system is a good example of this. It has an azimuth beamwidth of over 10 degrees, allowing for a smaller, less accurate antenna pointing system and lighter weight pedestal. As the size of the antenna decreases, however, reducing the relative size of the pedestal becomes less important. The 1-foot-diameter parabolic antenna that has been used as an example throughout this report is not likely to require a large

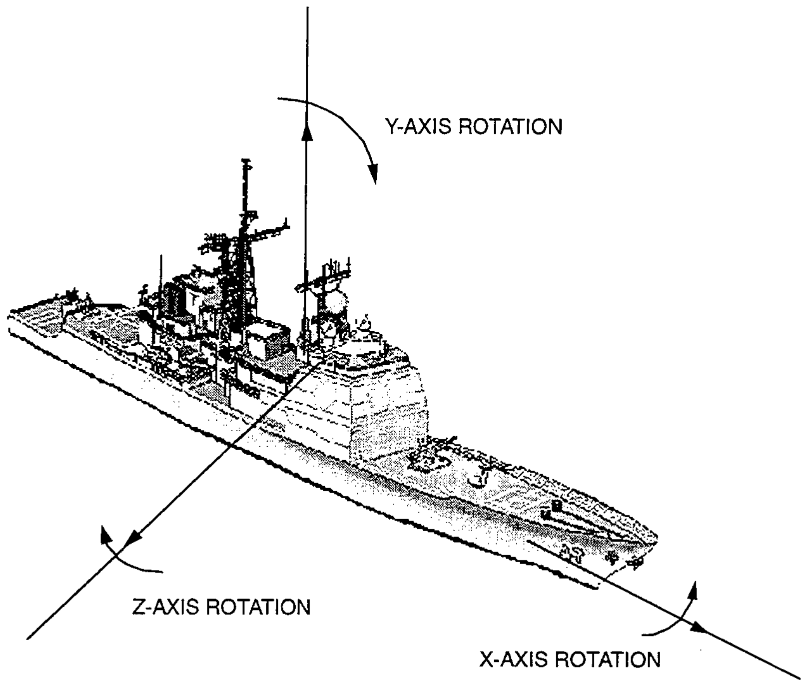

Figure 4. Shipboard axes rotation.

enough pedestal so that reducing its relative size would be crucial to being able to find a shipboard location for it. A specific example of this is the Millitech Series 3800 digital millimeter radio system (Millitech, 1995), with an antenna section that occupies a space measuring only 12 x 12 x 14 inches and weighing only 26 pounds.

Up to this point, we have only discussed parabolic dish antennas. For directional antennas, other options exist, such as Fresnel lenses, and conical and square horns. However, as discussed in Castro and Major (1988), practical implementations of these kinds of antennas do not exist that provide antenna gains much over 20 dB. There are a variety of reasons for this, such as the fact that as the aperture of a horn antenna grows, the electric field becomes less uniform at its mouth and more inefficiencies are introduced. Also, as the mouth of the horn antenna is increased, its length must increase as well, making large, high-gain horn antennas impractical due to their size.

Many commercial applications use extremely large parabolic dish antennas. These applications include satellite communications. As the gain of the antenna increases, the required output power of the satellite transmission system decreases. Since satellites are expensive to launch and more expensive as their weight increases, every dB of gain a ground station can provide means a dB less output power from the satellite and a potentially large savings in the launch cost.

However, the amount of gain obtained as the size of the dish is increased is an investment with diminishing returns. Gain for a parabolic antenna is given by:

$$G = 6.933 + 20 \log \left(\frac{D}{\lambda}\right), \tag{7}$$

where D is the diameter of the dish and λ is the wavelength of the signal. Figure 5 shows gain as a function of both frequency and antenna dish size. Note that the 20-dB line is crossed before 4.5 GHz, even for the 1-foot-diameter dish, which indicates that horn antennas are likely to be impractical for these applications. It is worth noting that commercial direct satellite TV systems are

only 1.5-foot dishes. A large amount of supporting equipment is available for these systems, including dynamic antenna pointing systems that might be used for shipboard antennas of this size.

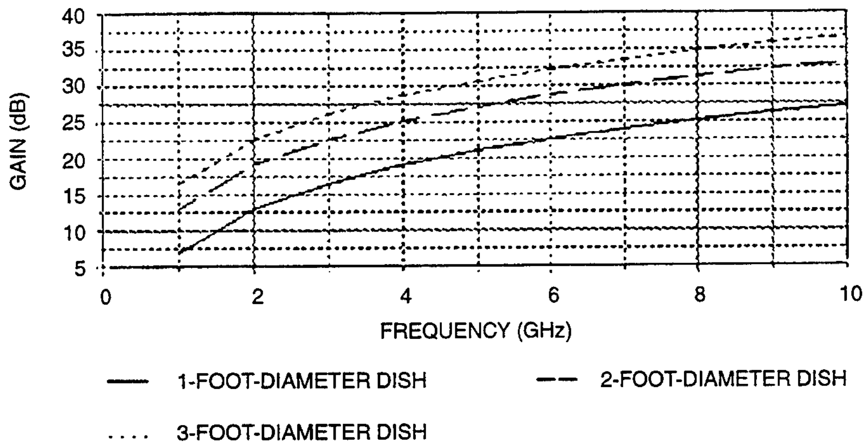

Figure 5. Antenna gain as a function of frequency and dish size.

As the size of the antenna increases, the beam becomes narrower. This can be a critical design variable for a shipboard antenna system, as the beamwidth of the antenna directly impacts the required accuracy of the antenna pointing system. Antenna beamwidth for a parabolic antenna is given by:

$$BW = \frac{58\lambda}{D}, \tag{8}$$

where D is the diameter of the dish and λ is the wavelength of the signal. Outside of this beamwidth, the attenuation is severe, with signal strength dropping off by 30 dB or more. Figure 6 shows beamwidth as a function of both frequency and antenna dish size. Tables 7 and 8 give parabolic antenna gain by frequency and dish diameter for 1 to 10 GHz and 5 to 90 GHz, respectively. Tables 9 and 10 give parabolic antenna beamwidth by frequency and dish diameter for 1 to 10 GHz and 5 to 90 GHz, respectively.

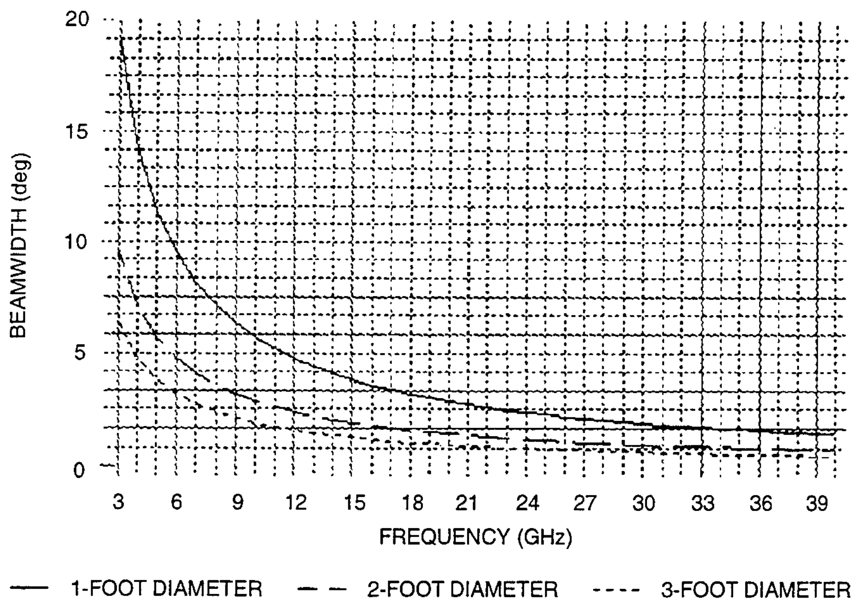

Figure 6. Antenna beamwidth as a function of frequency and dish size.

Table 7. Parabolic antenna gain by frequency and dish diameter, 1 to 10 GHz.

Frequency (GHz)	1 foot	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet
1	7.08	13.10	16.62	19.12	21.06	22.64	23.98
2	13.10	19.12	22.64	25.14	27.08	28.66	30.00
3	16.62	22.64	26.16	28.66	30.60	32.18	33.52
4	19.12	25.14	28.66	31.16	33.10	34.68	36.02
5	21.06	27.08	30.60	33.10	35.04	36.62	37.96
6	22.64	28.66	32.18	34.68	36.62	38.21	39.54
7	23.98	30.00	33.52	36.02	37.96	39.54	40.88
8	25.14	31.16	34.68	37.18	39.12	40.70	42.04
9	26.16	32.18	35.71	38.21	40.14	41.73	43.07
10	27.08	33.10	36.62	39.12	41.06	42.64	43.98

Table 8. Parabolic antenna gain by frequency and dish diameter, 5 to 90 GHz.

Frequency (GHz)	1 foot	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet
5	21.06	27.08	30.60	33.10	35.04	36.62	37.96
10	27.08	33.10	36.62	39.12	41.06	42.64	43.98
20	33.10	39.12	42.64	45.14	47.08	48.66	50.00
30	36.62	42.64	46.16	48.66	50.60	52.18	53.52
40	39.12	45.14	48.66	51.16	53.10	54.68	56.02
50	41.06	47.08	50.60	53.10	55.04	56.62	57.96
60	42.64	48.66	52.18	54.68	56.62	58.21	59.54
70	43.98	50.00	53.52	56.02	57.96	59.54	60.88
80	45.14	51.16	54.68	57.18	59.12	60.70	62.04
90	46.16	52.18	55.71	58.21	60.14	61.73	63.07

Table 9. Parabolic antenna beamwidth by frequency and dish diameter, 1 to 10 GHz.

Frequency (GHz)	1 foot	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet
1	57.033	28.516	19.011	14.258	11.407	9.505	8.148
2	28.516	14.258	9.505	7.129	5.703	4.753	4.074
3	19.011	9.505	6.337	4.753	3.802	3.168	2.716
4	14.258	7.129	4.753	3.565	2.852	2.376	2.037
5	11.407	5.703	3.802	2.852	2.281	1.901	1.630
6	9.505	4.753	3.168	2.376	1.901	1.584	1.358
7	8.148	4.074	2.716	2.037	1.630	1.358	1.164
8	7.129	3.565	2.376	1.782	1.426	1.188	1.018
9	6.337	3.168	2.112	1.584	1.267	1.056	0.905
10	5.703	2.852	1.901	1.426	1.141	0.951	0.815

Table 10. Parabolic antenna beamwidth by frequency and dish diameter, 5 to 90 GHz.

Frequency (GHz)	1 foot	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet
5	11.407	5.703	3.802	2.852	2.281	1.901	1.630
10	5.703	2.852	1.901	1.426	1.141	0.951	0.815
20	2.852	1.426	0.951	0.713	0.570	0.475	0.407
30	1.901	0.951	0.634	0.475	0.380	0.317	0.272
40	1.426	0.713	0.475	0.356	0.285	0.238	0.204
50	1.141	0.570	0.380	0.285	0.228	0.190	0.163

Table 10. Parabolic antenna beamwidth by frequency and dish diameter, 5 to 90 GHz. (Continued)

Frequency (GHz)	1 foot	2 feet	3 feet	4 feet	5 feet	6 feet	7 feet
60	0.951	0.475	0.317	0.238	0.190	0.158	0.136
70	0.815	0.407	0.272	0.204	0.163	0.136	0.116
80	0.713	0.356	0.238	0.178	0.143	0.119	0.102
90	0.634	0.317	0.211	0.158	0.127	0.106	0.091

SUMMARY

Recent technological advances in commercial microwave and millimeter communications afford the Navy an opportunity to expand its communications capabilities. High-data-rate, line-of-sight communications can be achieved through the use of microwave and millimeter communications systems that give the Navy access to large amounts of the frequency spectrum that are currently unused. Through the use of commercially available communications equipment, with minor modifications for operation in a shipboard environment, the Navy might be able to realize a high-data-rate, point-to-point network in the near term at frequencies below 30 GHz. Rain attenuation appears to be a severe limiting factor of communication ranges above 30 GHz.

Appendices A and B give a brief list of commercially available candidate equipment and address possible operation concepts for such systems.

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APPENDIX A
CANDIDATE DEMONSTRATION SYSTEM

Commercial applications of microwave and millimeter LOS communications have led to the development of a wide variety of communications systems. The candidate systems given below are not exhaustive by any means, but are intended to give the reader an idea of the kinds of commercial systems currently available. Also, these systems have not been analyzed in detail to determine which, if any, match the current needs of the U.S. Navy.

The systems that can be assembled from the components given below are intended to be used as a part of the Communications Support Systems (CSS) infrastructure, providing CSS elements with a high-data-rate, point-to-point physical layer information transport. To support this, some modifications might be necessary to the CSS Channel Access Protocol (CAP) hardware and software, but such modifications are unlikely to be extensive as CAPs already exist for HF and UHF LOS applications.

Item: Full-duplex digital/analog radio with antenna
Company: Millitech
Product Name: Series 3800
Specifications: 26- to 40-GHz radio system with data rates up to 20 Mbps. 100-mW transmit power, 60-MHz intermediate frequency, 30-MHz bandwidth. 10-inch Fresnel lens antenna with 35-dB gain and 2.5-degree beamwidth.

Item: Digital Microwave Radio
Company: Loral TerraCom
Product Name: TCM-640
Specifications: 1.7- to 19.7-GHz radio system with data rates up to 45 Mbps. 100-mW to 3-W transmit power, 70-MHz intermediate frequency, 5- to 40-MHz bandwidths. Antenna separate.

Item: Digital Microwave System
Company: Microwave Radio
Product Name: MR-40DR
Specifications: 36- to 40-GHz radio system with data rates up to 8 Mbps. 50-mW transmit power, 70-MHz intermediate frequency, 14-MHz bandwidth. 12-inch parabolic antenna with 38-dB gain and 2-degree beamwidth.

Item: High-Capacity Digital Radio
Company: Alcatel
Product Name: Collins MDR-4X11e
Specifications: 10.7- to 11.7-GHz radio system with data rates up to 135 Mbps. 500-mW transmit power, 15- to 30-MHz bandwidth. Antenna separate.

Item: Digital Microwave Radio
Company: TeleSciences
Product Name: Telestar 23-672
Specifications: 21.2- to 23.6-GHz radio system for analog signal transmission. Can be paired with modem for digital transmissions. Up to 65-W transmit power, 230-MHz intermediate frequency, 50-MHz bandwidth. 2-foot-diameter parabolic antenna with 40-dB gain and 1.7-degree beamwidth.

Item: Telemetry Autotracking Antenna System
Company: Datron
Product Name: Series 1000
Specifications: High-velocity antenna tracking system with angular velocity of 45 degrees per second. Can function with antennas as large as 8 feet in diameter.

Item: Conical Scan Antennas
Company: Alpha Industries, Inc.
Product Name: Series 832/833
Specifications: 12.4- to 220-GHz conical dish antenna in sizes from 12- to 48-inch diameter. 12-inch dish gain is better than 30 dB with 2-degree beamwidth.

APPENDIX B
HYPOTHETICAL CONCEPT OF OPERATIONS

Due to the flexibility afforded by the large data rates supported by the communications systems described in this document, they can be used for a wide variety of applications. The following list gives a sample of applications that might be of immediate interest to the Navy.

NON-TIME-CRITICAL DATA UPDATES

Much of the communications that goes on between ships is not time-critical. The transmission of administrative messages, logistical messages, electronic mail, and computer data files could be offloaded from current communications gear and performed by these systems, leaving the other systems available for time-critical communications such as voice and tactical data traffic. An entire day's worth of such data could be exchanged by these high-data-rate systems in minutes or even seconds.

As an example, say a ship currently has four 9600-baud UHF channels and four 2400-baud HF channels available to it. If they were all used 24 hours a day, they would be able to transfer a total of about 4147 megabits. A single 20-Mbps link would be able to transfer this data in less than 4 minutes. Clearly, such a capacity would increase the size and number of digital transmissions possible within a battlegroup. While these links only allow point-to-point communications, through the use of point-to-point networking techniques, data intended for a ship that was not within line of sight of the data source ship could be relayed from ship to ship until the destination was reached.

LONG-HAUL VIDEO TELECONFERENCING

Many of the Navy's capital ships have access to high-data-rate satellite communications. Ships equipped with such systems have been able to perform video teleconferencing (VTC) with nodes across the world. If the members of the capital ship's battlegroup were equipped with the high-data-rate systems described in this document, the VTC digital stream could be routed from the capital ship to the smaller vessels, allowing them to participate in the VTCs as well. This technique has already been demonstrated using high-data-rate UHF LOS links developed at NRaD.

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This document addresses potentials for Navy use of line-of-sight (LOS) communication links in the microwave and millimeter frequency bands (2 GHz to 90 GHz) to support data rates greater than 10 Mbps. Issues relevant to communications in this frequency band are addressed, such as weather effects, LOS blockage, and the need for high-gain directional antennas. Additionally, Navy-specific issues are discussed, including size and weight limitations, shipboard electromagnetic interference sources, and antenna stabilization aboard moving platforms.

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